PREDICTING WATERSHED POST-FIRE SEDIMENT YIELD WITH THE InVEST SEDIMENT RETENTION MODEL: ACCURACY AND UNCERTAINTIES

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Abstract: Increased sedimentation following wildland fire can negatively impact water supply and water quality. Understanding how changing fire frequency, extent, and location will affect watersheds and the ecosystem services they supply to communities is of great societal importance in the western USA and throughout the world. In this work we assess the utility of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) Sediment Retention Model to accurately characterize erosion and sedimentation of burned watersheds. InVEST was developed by the Natural Capital Project at Stanford University (Tallis et al., 2014) and is a suite of GIS-based implementations of common process models, engineered for high-end computing to allow the faster simulation of larger landscapes and incorporation into decision-making. The InVEST Sediment Retention Model is based on common soil erosion models (e.g., USLE – Universal Soil Loss Equation) and determines which areas of the landscape contribute the greatest sediment loads to a hydrological network and conversely evaluate the ecosystem service of sediment retention on a watershed basis. In this study, we evaluate the accuracy and uncertainties for InVEST predictions of increased sedimentation after fire, using measured post-fire sediment yields available for many watersheds throughout the western USA from an existing, published large database. We show that the model can be parameterized in a relatively simple fashion to predict post-fire sediment yield with accuracy. Our ultimate goal is to use the model to accurately predict variability in post-fire sediment yield at a watershed scale as a function of future wildfire conditions.

INTRODUCTION

Fire suppression and the increased accumulation of fuels over the last century has led to a greater risk of high severity wildland fires for many watersheds of the western USA. Future climate change in the form of warmer temperatures and altered precipitation regimes may further increase wildfire potential (Flannigan et al., 2000, Westerling et al. 2006). Wildfire can impact watersheds through changes in the timing and amount of runoff, and increased erosion and sedimentation (Miller et al., 2011). These processes can negatively affect water quality, water supply, and other important ecosystem services such as sediment retention, which is a measure of the capacity for a watershed to withstand erosion and sedimentation.

When fire occurs on a landscape, burning immediately alters the existing distribution and structure of vegetation (Larsen et al., 2009). Vegetation can slow down overland flow of water and reduce the erosive force and sediment transport capacity of water. Vegetation can also trap and filter sediment transported by water. Collectively, these characteristics of vegetation contribute to the ability of a watershed to retain sediment, which results in the afore-mentioned ecosystem service. Combustion of vegetation thereby reduces watershed sediment retention.

Burning also directly alters soil characteristics (González-Pérez et al., 2004). Depending on the intensity of heat during a fire, soil organic content can be reduced and clay particles can become aggregated into fine silt-sized particles (Giovannini et al., 2001). The loss of organic material and a litter layer that otherwise provide a protective shield to the soil surface can increase soil erosion through increased exposure to rain splash, decreased infiltration, and increased sheet wash and rill erosion (DeBano, 2000). Intense heat also changes the carbon and nitrogen balance in soil, and can trigger a reduction in microbial activity (Choromanska and DeLuca, 2002). Collectively, these factors can increase erodibility of soil post-fire. In addition to post-fire changes in vegetation, increased erodibility further decreases watershed sediment retention.

The ability to efficiently and accurately model sediment retention at the scale of individual watersheds for a large number of watersheds is important (Miller et al., 2011). It provides a tool for resource managers to better understand and simulate how fire effects on vegetation and soil may affect the ecosystem service of sediment retention or conversely, post-fire sediment yield. The InVEST suite of ecosystem service models are an open source, stand-alone platform developed by Stanford University as part of the Natural Capital Project. The Sediment Retention model is designed to evaluate sediment retention at a watershed scale to enable the assessment of tradeoffs for natural resource management decisions (Tallis et al., 2014). The Sediment Retention model can be used to simulate how changes in vegetation and soil erodibility, which occur as a function of landscape processes such as fire, may affect watershed sediment retention or sediment yield. Moreover, the InVEST predictions under different scenarios of vegetation and soil condition can be evaluated as indicators of the potential relative change in the ecosystem service as a function of wildfire. The GIS-based Sediment Retention model implements the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) to predict annual potential erosion at the pixel scale and annual sedimentation and retention at the watershed scale. The model takes into account landform, climate, soil, and vegetation properties. Users can also assess the influence of different vegetation types and soil properties.

For the western USA, Moody and Martin (2009) completed a comprehensive and exhaustive review and synthesis of measured post-fire sediment yields (Figures 1 and 2). Their study divided the western United States into four regions based on rainfall regimes: Pacific, Sub-Pacific, Arizona, and Plains, which vary by seasonal distribution of rainfall; and with sub-categories of Extreme, High, Medium, and Low rainfall intensity. Within these regions they identified all of the published measurements of post-fire sediment yield. The synthesis identified 135 measurements in 43 unique watersheds (defined at the Hydrologic Unit Code 8 “HUC-8” level) that spanned post-fire episodes from 1927 to 2007. They further identified whether the measurements were conducted on hillslope or channel landscape positions, whether they were conducted at point or plot scales, and whether they targeted a specific range of particle size and/or transport mechanism. This resulted in a classification of each measurement into one of four types: Hillslope Points (H-Pt), Hillslope Plots (H-Plot), Channel Suspended Sediment (CSS), and Channel Volume (C-V) measurements (Moody and Martin, 2009). The Moody and Martin (2009) synthesis of post-fire sedimentation provides a baseline of field data to calibrate sediment yield predictions made with the InVEST Sediment Retention model in our study (Figures 1 and 2).

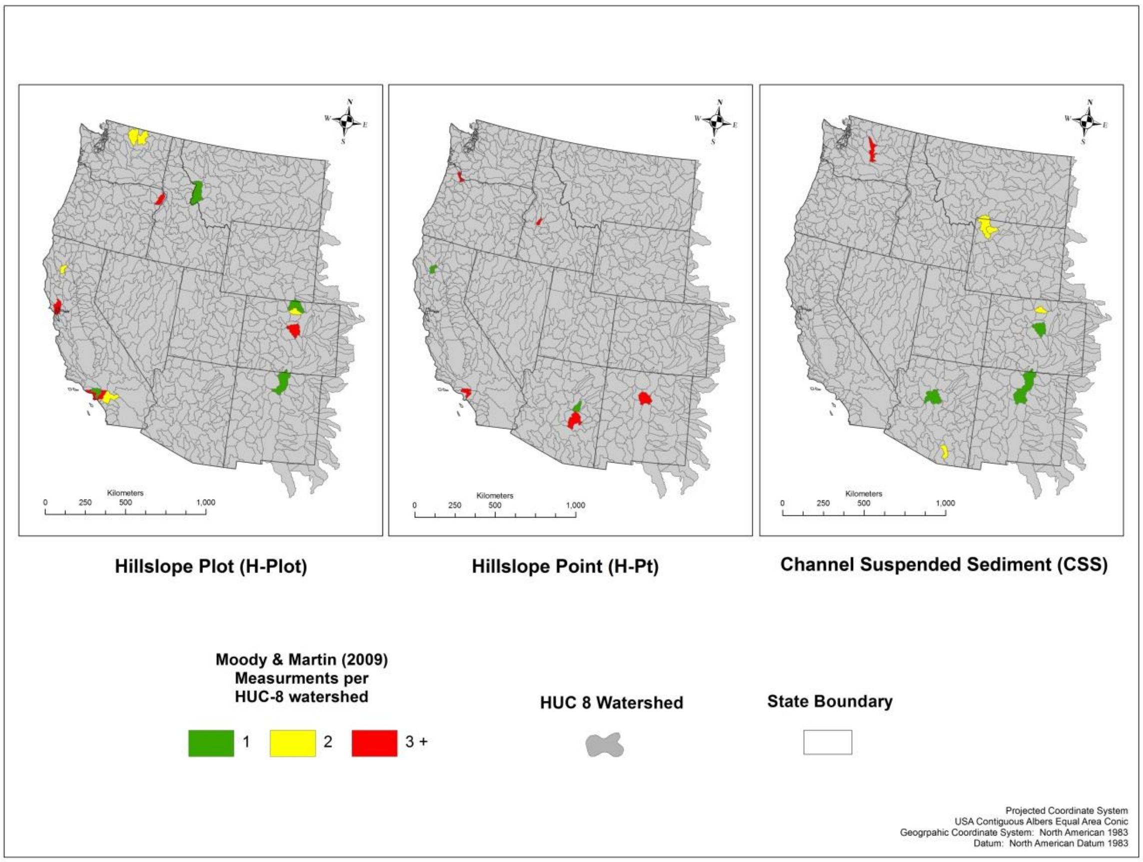

Figure 1 Number of hillslope plot (H-Plot), point (H-Pt), and channel suspended sediment (CSS) measurements synthesized by Moody and Martin (2009) per HUC-8 watershed in the western USA.

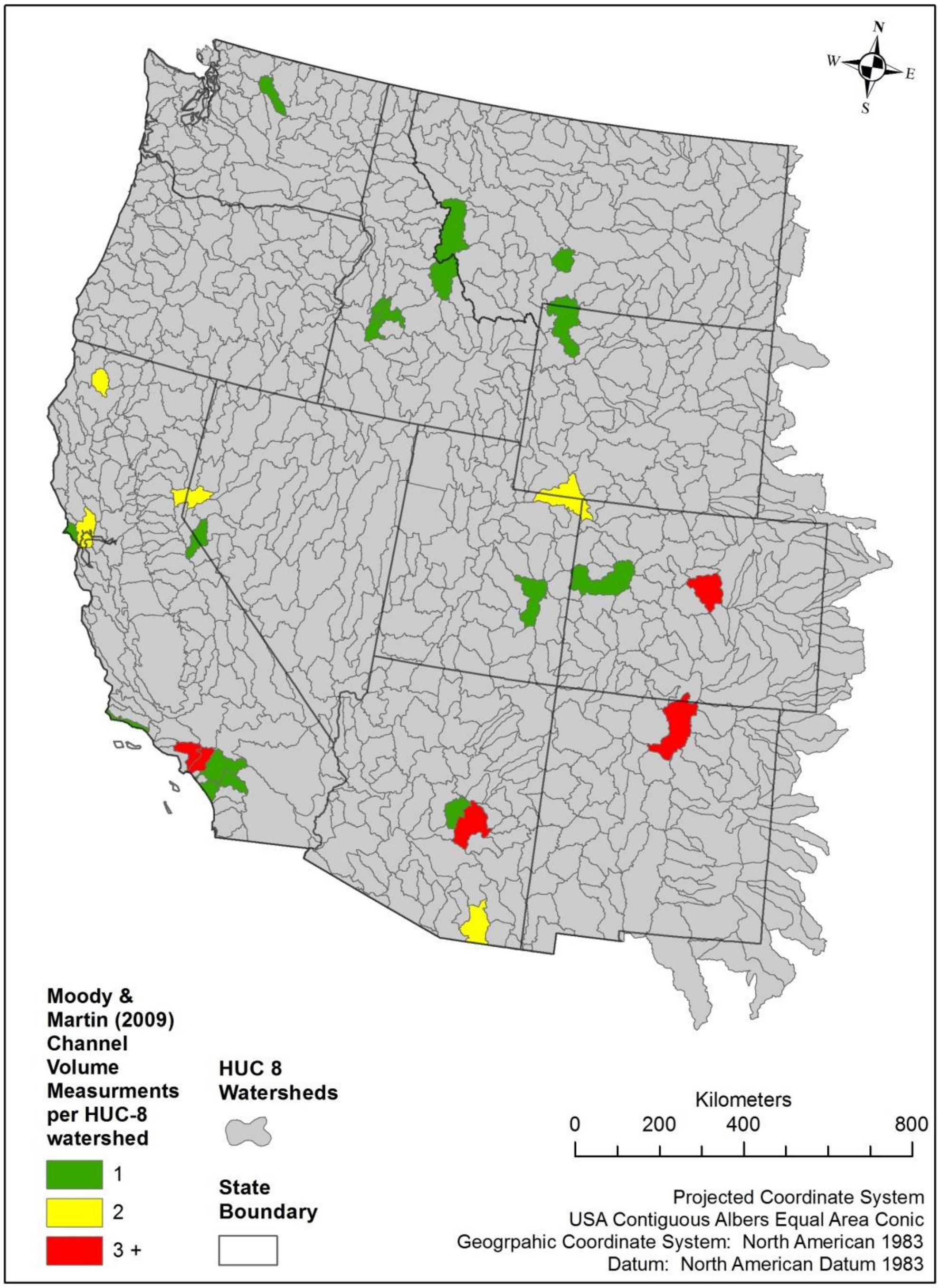

Figure 2 Number of channel volume (CV) measurements synthesized by Moody and Martin (2009) per HUC-8 watershed in the western USA.

OBJECTIVE

In this study, our primary objective was to parameterize and calibrate the InVEST Sediment Retention model to predict post-fire sediment yield at a watershed-scale as accurately as possible. We used measured post-fire sediment yields for watersheds reviewed in the Moody and Martin (2009) synthesis as the baseline calibration data set. We evaluated the relative ability of the model to accurately predict sediment yield for the 4 different types of measurements identified by Moody and Martin (2009). Because the Sediment Retention model is a watershed-scale model we hypothesized that it would most accurately predict measurements made within channel landscape positions (CSS or C-V), which presumably integrate over a greater upslope area of the watershed, than measurements made on hillslopes at plots (H-Plot) or points (H-Pt) within the watershed. Moreover, we hypothesized that the Sediment Retention model would most accurately predict channel volume (C-V) as opposed to channel suspended sediment (CSS) measurements because the model is not designed to target the more narrowly defined range of particle size fractions of sediment transported in suspension. Therefore, we first determined the best-fit parameter set for the particular measurement type that we identified as most appropriate through tests of the aforementioned hypotheses. Then we used the calibrated Sediment Retention model to predict sediment yield response to wildfire for all HUC-8 watersheds across the western United States.

METHODS

We predicted watershed sediment yield (tons/HA) with the InVEST Sediment Retention model for watersheds delineated at the HUC-8 level in the western USA (USGS, www.water.usgs.gov). In order to predict sediment yield, the Sediment Retention model requires Digital Elevation Model (DEM), land use/land cover (LULC), Soil Erosivity (R-Factor), and Soil Erodibility (K-Factor) raster datasets. The model requires a vector dataset that defines the watershed boundaries, and several user-defined tables that characterize important biophysical characteristics of the watersheds.

We used a 90 m resolution DEM (USGS, seamless.usgs.gov) with stream networks from the USGS National Hydrography Dataset (USGS, nhd.usgs.gov) “burned” in and small holes filled using the InVEST toolbox for ArcGIS. We used the National Land Cover Dataset (NLCD) 2006 (USGS, www.mrlc.gov) which has 16 land cover classes at 30 m resolution as the LULC raster.

The R-factor is a climatic indicator that estimates the kinetic energy of rainfall at the maximum 30 minute intensity. We converted an R-Factor vector layer produced by the Environmental Protection Agency (EPA) at the HUC-8 scale (EPA, www.epa.gov), to a 30-m R-Factor raster using a (multiplication) factor of 17.02 to convert from imperial to metric units (Tallis et al., 2014).

The K-Factor is an estimate of soil erodibility as a function of soil development and horizonation, texture, organic matter, and permeability. This was created from the State Soil Geographic Database (STATSGO) K-Factor vector data (USDA, Natural Resources Conservation Service; www.nrcs.usda.gov) and transformed into a 30-m raster dataset.

The Sediment Retention model requires a biophysical table characterizing response by land use/land cover type. Variables in the table include the sediment retention efficiency value which characterizes the relative ability of the vegetation type to slow down overland flow and trap and filter sediment transported by water. The sediment retention efficiency is a floating point index from 0 to 1, where 0.0 = minimum, and 1.0 = maximum, sediment retention. The biophysical table also includes the cover-management factor (C), and the support practice factor (P) values from the USLE. The C and P factors are important agricultural metrics that account for cover crop management and tilling practices, but were not integral to this study. As our study focused on pre- and post-fire conditions for a range of landcover types throughout the western USA, C and P factors were left at default values for all classes and all watersheds (Tallis et al., 2014).

A sediment threshold table containing information about expected reservoir lifetime, water volume, and annual sediment load is required for the intended assessment of the effect of sedimentation on hydropower, but not necessary to modify for our predictions of sediment yield. For the purpose of the table, we treated each watershed as the catchment area for a single reservoir and left default values in place (Tallis et al., 2014).

The Sediment Retention model takes into account a user-defined threshold flow accumulation number, which is the number of upstream pixel cells that must flow into a cell before it is counted as part of the stream network. The threshold flow accumulation number is therefore important for accurately characterizing the watershed drainage network. The Sediment Retention model also requires a slope threshold, which is included to account for agricultural landscapes on steep hillslopes. We heuristically experimented with different values for these variables but ultimately used the default of 1000 cells for threshold flow accumulation, and 75% slope threshold (Tallis et al., 2014).

We first predicted sediment yield for each HUC-8 watershed in the western USA using the aforementioned data and recommended default settings (Tallis et al., 2014). Next, we adjusted vegetation and soil characteristics in the input datasets in order to predict sediment yield for simulated post-fire characteristics of vegetation and soil. We specifically set the sediment retention efficiency value (i.e., of vegetation) to 0.0 for each watershed in the biophysical table, and we increased the soil erodibility (K) by one order of magnitude. These sediment retention and soil erodibility values were intended to simulate an extreme effect of fire in which the ability for vegetation to retain sediment is negated and soil erodibility is dramatically increased. These sediment retention efficiency and soil erodibility values were found heuristically to best predict measured sediment yield in the synthesis by Moody and Martin (2009). We compared sediment yield predicted with the InVEST model using the adjusted sediment retention and soil erodibility values to measured sediment yield reported in Moody and Martin (2009) for each HUC-8 watershed that contained at least one reported sediment yield measurement. We compared predictions to measurements aggregated by type (H-Pt, H-Plot, CSS, C-V) for each watershed. For watersheds with more than 1 measurement of a given type we calculated the mean of measured values of post-fire sediment yield by measurement type (which in some cases included unique measurements of the same type and within the same watershed but from multiple fires during the past century). To evaluate the accuracy of model predictions we focused on watersheds that had at least 3 post-fire measurements per type (Figures 1 and 2), and compared the mean measured post-fire watershed sediment yield to the yield predicted with the InVEST

Sediment Retention model using linear regression and by calculating an average prediction error (Root Mean Squared Error – RMSE).

RESULTS

InVEST model predictions of post-fire sediment yield were not significantly related to sediment yield measurements made with the C-SS, H-Plot, or H-Pt methods and reported in Moody and Martin (2009) (results otherwise not shown). The model accurately predicted mean post-fire sediment yield for those watersheds (n = 5) with at least 3 discrete channel volume (C-V) measurements reported in the Moody and Martin (2009) synthesis (Figure 3). The model accurately predicted approximately 50% of the variability in the mean C-V measurements. The RMSE average prediction error for these 5 watersheds (N ≥ 3 post-fire C-V measurements) was 149.29 tons/HA. The variance of reported channel volume measurements appeared to be large for some watersheds (e.g., standard error bars for measurement means in Figure 3) relative to the average prediction error of the model. Maps in Figures 4 and 5 show predicted sediment yield for all HUC-8 watersheds of the western USA based on: 1) the default parameters (Figure 4) for the InVEST Sediment Retention model (described in Methods section); and 2) the adjusted sediment retention efficiency and erodibility (K) values intended to simulate post-fire vegetation and soil conditions (Figure 5).

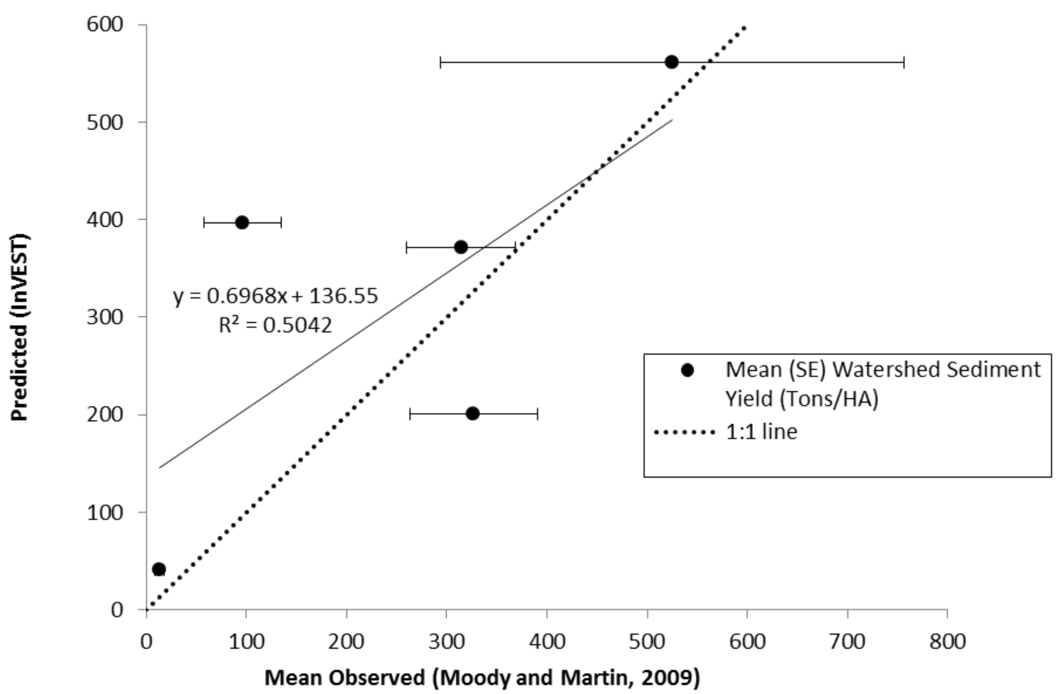

Figure 3 Post-fire sediment yield (tons/ha) predicted with InVEST plotted as a function of mean measured post-fire channel volume sediment yield for watersheds with at least 3 measurements reported in Moody and Martin (2009).

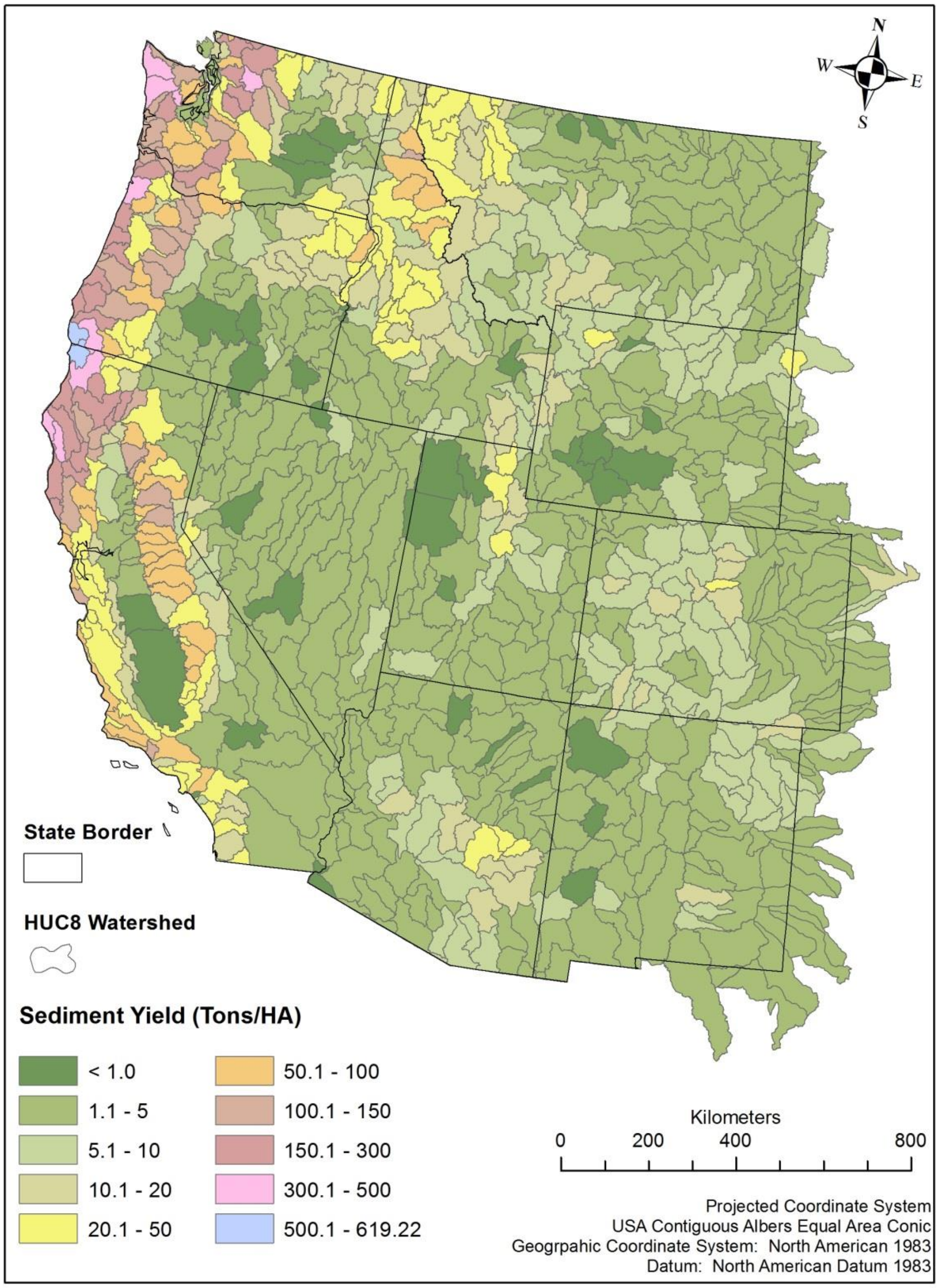

Figure 4 InVEST modeled sediment yield (tons/ha) for all HUC-8 watersheds using normal (default) input parameters.

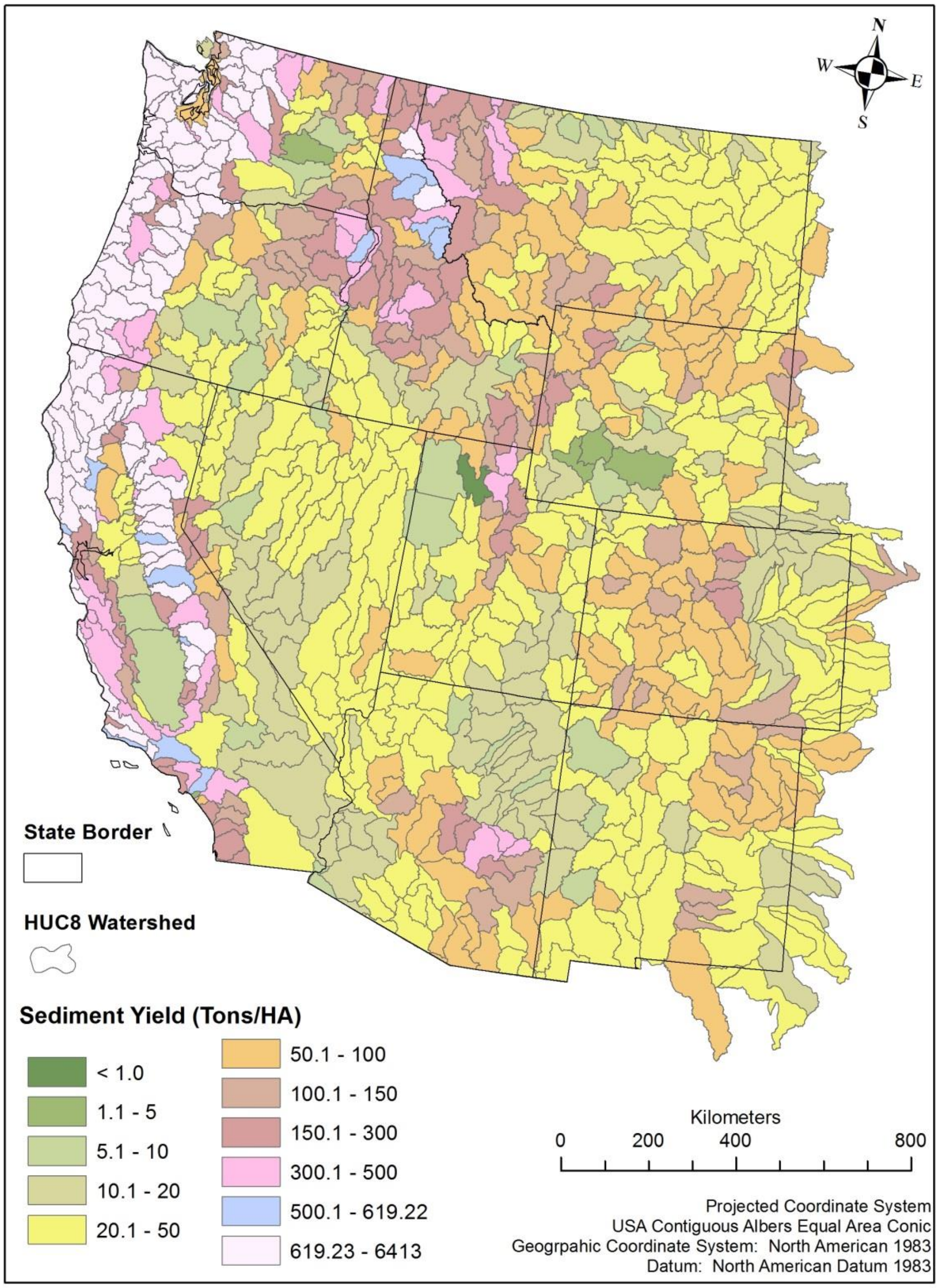

Figure 5 InVEST modeled sediment yield (tons/ha) for all HUC8 watersheds using input parameters modified to simulate post-fire conditions.

DISCUSSION

We evaluated the relative ability of the InVEST Sediment Retention model to accurately predict 4 different classes of post-fire sediment yield measurements synthesized for the western USA by Moody and Martin (2009). Channel volume measurements were the only measurement type for which we determined a significant relationship between model predictions and measured values of post-fire sediment yield. One explanation for why the InVEST Sediment Retention model might predict channel volume measurements with accuracy is because it is a watershed-scale model and measurements made within channel landscape positions are likely to integrate over a larger upstream area and are thus more comparable to the model domain; compared for example to measurements made on hillslopes (plots or point locations) within the watershed. The Sediment Retention model is not designed to predict specific ranges of particle sizes and therefore might also more accurately predict variability in channel volume measurements because they are not comprised of, or constrained to, a specific and narrow particle size range.

Relevant limitations of the model for predicting post-fire sediment yield are that it is based on the USLE and is designed to predict sedimentation as a function of sheet-wash erosion processes, but not from other erosion processes such as rilling, gullying, debris flows or other mass-wasting events (Tallis et al., 2014). The sediment retention efficiency index value that is parameterized by the model user for each LULC class has been identified as another potential limitation for prediction accuracy because few spatially explicit data at the relevant watershed scale are available to accurately characterize the biophysical interactions between vegetation, erosion, and sedimentation (Tallis et al., 2014). There are also few spatially explicit data that describe how the K factor varies as a function of fire within and among watersheds across such a large region; though soil erodibility is certainly known to increase with burning (DeBano, 2000; Giovannini et al., 2001).

Our parameterization of the model resulted in predictions that explained variability in post-fire sediment yield at a watershed-scale for the channel volume measurement type reviewed by Moody and Martin (2009). We anticipate that the methodology presented here for predicting post-fire sediment yield with the InVEST Sediment Retention model will have utility for evaluating the relative, potential vulnerability of watersheds to increased sedimentation as a function of future changes in wildfire frequency and occurrences throughout the western USA.

CONCLUSION

The InVEST Sediment Retention Model provides a GIS platform to efficiently model sediment yield and the ecosystem service of sediment retention at a watershed scale for a large number of watersheds. In this study, we showed that the model can be parameterized in a relatively simple fashion to predict post-fire sediment yield using site data where sediment yield measurements are characteristic of watershed-scale erosion and sediment delivery. Future work will focus on using the InVEST suite of models to assess tradeoffs for natural resource management decisions and to evaluate the potential vulnerability of watersheds throughout the western USA to post-fire sedimentation as a function of future changes in wildfire frequency and occurrence.

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